

# Probing the Anomalous Couplings of the Top Quark with Gluon at the LHC and Tevatron

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## Abstract

In this paper, we study the sensitivity of the fraction of  $t\bar{t}$  events arising from gluon-gluon fusion to the chromoelectric and chromomagnetic dipole moments (CEDM and CMDM) as well as the  $t\bar{t}$  cross sections at the LHC and Tevatron, and the recently measured charged asymmetry at the LHC. We find that at the Tevatron and the LHC, non-zero values of CMDM could suppress the  $t\bar{t}$  production rate. It is shown that the ratio of  $\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$  at the Tevatron is more sensitive to CEDM and CMDM than the LHC case. The presence of CEDM always increases the contribution of gluon-gluon fusion process in top pair rate at the Tevatron and LHC. Except for a small range of CMDM, the presence of CEDM and CMDM can increase the fraction of gluon-gluon fusion at the Tevatron and LHC. The measured ratio of  $\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$  at the Tevatron is used to derive bounds on the chromoelectric and chromomagnetic dipole moments as well as the cross sections at the LHC and Tevatron, and the measured charged asymmetry at the LHC.

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# 1 Introduction

From the point of view of the large mass of the top quark, it could provide excellent probes of the electroweak symmetry breaking mechanism as well as clarifying the nature of any force and any particle responsible for this phenomenon. Furthermore, the top quark production and decay rates can also prepare a good place to probe possible new parity violating and anomalous CP violating interactions which could be induced by non-SM particles [1],[2],[3].

The top quark couplings still need to be measured more precisely to be able to observe any deviations from the standard model predictions. In particular, the anomalous interactions between the top quark and gauge bosons can influence the top quark production cross sections at high energy colliders such as the Large Hadron Collider (LHC) and Tevatron.

The beyond standard model effect in the production of  $t\bar{t}$  could be parameterized in a rather model independent way by effective couplings of quark-gluon, which indeed may be induced by exchange of heavy particles.

The  $t\bar{t}$  production at hadron colliders is obviously the only place for *direct* search of anomalous  $gt\bar{t}$  interactions. In this analysis, in particular, we concentrate on the study of top quark chromomagnetic and chromoelectric couplings that are described by the following effective Lagrangian:

$$\mathcal{L}_{t\bar{t}g} = \frac{ig_s}{2m_t} \bar{t} \sigma_{\mu\nu} q^\nu (\kappa - i\tilde{\kappa}\gamma_5) t G^\mu \quad (1)$$

where  $g_s$  is the strong coupling constant,  $q^\nu$  is the 4-momentum of the involved gauge boson (gluon), and  $G^\mu$  is the gluon gauge field. It is worth mentioning that due to the excellent agreement between the SM expectations and the present experimental data, any deviations from the SM are small. Accordingly, the new effective terms must be very small and the interference term between SM and new effective terms could be big enough to be measured.

Please note that  $\kappa$  and  $\tilde{\kappa}$  are loosely referred as the CMDM and CEDM form factors but they are related to the dimensionful CMDM and CEDM via the following equations:

$$\kappa = \frac{2m_t}{g_s} \mu_t^g, \quad \tilde{\kappa} = \frac{2m_t}{g_s} d_t^g \quad (2)$$

In renormalizable theories  $\kappa$  and  $\tilde{\kappa}$  are induced at loop level. Notice that non-zero value for  $\tilde{\kappa}$  leads to CP violating interactions. The generated chromoelectric moment (CEDM) by the

CKM phase is very small. Therefore, the measurement of observables that signify CP violation in top pair production using large statistics data should be studied carefully.

In the SM, at one-loop level the QCD corrections generate CMDM via gluon exchange in two distinct Feynman diagrams. One of the diagrams is quite similar to the QED case (with replacement of photon with gluon) and another one consists of an external gluon which is coupled to the internal gluons which is because of the non-abelian nature of QCD. Similar to QED, these diagrams generate CMDM proportional to  $\alpha_s/\pi$  (but after replacing  $\alpha_{em}$  by  $\alpha_s$ ). There is an overall factor which is originating from the multiplication of color matrices. It should be indicated that in addition to QCD corrections, Higgs and  $Z$  boson exchanges generate CMDM [4],[5].

So far, there have been several studies on the anomalous chromoelectric and chromomagnetic dipole moments. The CEDM and CMDM effects on the top pair and single top cross sections and other related observables at hadron colliders were examined in [6], [7],[8],[9],[10],[11],[12],[13]. It was shown that the  $t\bar{t}$  differential cross section (such as transverse momentum and invariant mass of  $t\bar{t}$ ) is sensitive to the sign of CMDM as well as its size. Possible range on  $\kappa$  using 30 fb<sup>-1</sup> of future  $e^-e^+$  collider with 500 GeV center-of-mass energy is  $-2.1 < \kappa < 0.6$  [14].

Apart from the direct study of CMDM and CEDM at hadron colliders in  $t\bar{t}$  events, they can modify the decay rate of  $B \rightarrow X_s \gamma$  [15],[16] at loop level. Using the measured branching ratio of  $Br(b \rightarrow s \gamma)$ , tight bounds on  $\kappa$  was extracted. The limit is  $-0.03 < \kappa < 0.01$ .

In specific models, such as minimal supersymmetric standard model (MSSM), little Higgs model, and two-Higgs doublet model, non-zero  $\kappa$  could be generated [17],[18],[19]. For example, in a specific parameter space of MSSM, the corrections to CMDM can be as large as 20%. In [19], the authors have calculated the one-loop contributions of the new particles of the littlest Higgs model with T-parity to the top quark chromomagnetic dipole moment (CMDM). It was shown that the CMDM that is generated by this model is one order of magnitude smaller than the SM predicted value. In [20], the effect of unparticle to the chromomagnetic dipole moment (CMDM) of the top quark has been studied. The induced effects by scalar and vector unparticle operators were computed on the CMDM. It was shown that depending on the parameters space and couplings, unparticle could suppress the chromomagnetic dipole moment. In [9], a class of technicolor models was proposed that contains techniscalars which may produce large values of

chromomagnetic dipole moments for the top quark as well as examining the dependency of the differential and the cross section of  $t\bar{t}$  on  $\kappa$ .

In this paper, in addition to the total cross section of  $t\bar{t}$  at the LHC and Tevatron, we use the measured ratio of cross section of  $t\bar{t}$  arising from gluon-gluon fusion to the total  $t\bar{t}$  cross section to study the allowed region of parameters  $\kappa$  and  $\tilde{\kappa}$ . The sensitivity of recently measured charge asymmetry in top pair events at the LHC is also examined to the anomalous couplings of top quark to gluon.

## 2 Influence of CEDM and CMDM on the $t\bar{t}$ Cross Section

The effective Lagrangian approach is specially useful when the underlying new physics is not known. The effective Lagrangian for describing the interaction between the top quark and a gluon, which considers the CEDM and CMDM form factors of the top quark, was introduced in Eq.1. An important point is that the effective interaction of  $ttgg$  which is absent in the SM must be taken into account to ensure gauge invariance.

The  $t\bar{t}$  production at hadron colliders ( $pp(\bar{p}) \rightarrow t\bar{t}$ ) can proceed at partonic level through quark-antiquark annihilation ( $q\bar{q} \rightarrow t\bar{t}$ ) or gluon-gluon fusion ( $gg \rightarrow t\bar{t}$ ). The parton level cross sections for  $gg \rightarrow t\bar{t}$  and  $q\bar{q} \rightarrow t\bar{t}$  has the following forms [6]:

$$\frac{d\hat{\sigma}_{q\bar{q} \rightarrow t\bar{t}}}{d\hat{t}} = \frac{8\pi\alpha_s^2}{9\hat{s}^2} \left[ \frac{1}{2} - f(\hat{s}, \hat{t}) + g(\hat{s}) - \kappa + \frac{\kappa^2}{4} \left( 1 + \frac{f(\hat{s}, \hat{t})}{g(\hat{s})} \right) + \frac{\tilde{\kappa}^2}{4} \left( \frac{f(\hat{s}, \hat{t}) - 1}{g(\hat{s})} \right) \right] \quad (3)$$

$$\begin{aligned} \frac{d\hat{\sigma}_{gg \rightarrow t\bar{t}}}{d\hat{t}} &= \frac{\pi\alpha_s^2}{12\hat{s}^2} \left[ \left( \frac{4}{f(\hat{s}, \hat{t})} - 9 \right) \left( \frac{1}{2} - f(\hat{s}, \hat{t}) + 2g(\hat{s}) \left( 1 - \frac{g(\hat{s})}{f(\hat{s}, \hat{t})} \right) - \kappa \left( 1 - \frac{\kappa}{2} \right) \right) \right. \\ &\quad + \frac{1}{4} (\kappa^2 + \tilde{\kappa}^2) \left( \frac{7}{g(\hat{s})} (1 - \kappa) + \frac{1}{2f(\hat{s}, \hat{t})} \left( 1 + \frac{5\kappa}{2} \right) \right) \\ &\quad \left. + \frac{1}{16} (\kappa^2 + \tilde{\kappa}^2)^2 \left( \frac{1}{f(\hat{s}, \hat{t})} - \frac{1}{g(\hat{s})} + \frac{4f(\hat{s}, \hat{t})}{g^2(\hat{s})} \right) \right] \end{aligned} \quad (4)$$

where

$$f(\hat{s}, \hat{t}) = \frac{(\hat{t} - m_t^2)(\hat{u} - m_t^2)}{\hat{s}^2}, \quad g(\hat{s}) = \frac{m_t^2}{\hat{s}^2}, \quad \hat{s} + \hat{t} + \hat{u} = 2m_t^2 \quad (5)$$

According to the parton level cross section, in spite of CMDM ( $\kappa$ ), the cross-section is expected to be symmetric with respect to CEDM ( $\tilde{\kappa}$ ). Since the cross section is not a CP violating observable,  $\tilde{\kappa}$  enters in the cross section in even powers.

It is notable that the contribution of the CEDM and CMDM to the partonic differential cross sections of  $gg \rightarrow t\bar{t}$  and  $q\bar{q} \rightarrow t\bar{t}$  grows with  $\hat{s}$ . In general, the new couplings could be dependent on  $\hat{s}$ . However, if the new physics scale is much higher than  $\sqrt{\hat{s}}$ , we can neglect any dependence of CEDM and CMDM on  $\hat{s}$ . The increase of center-of-mass energy reduces the reliability of the assumption of constantness of the CEDM and CMDM.

The hadronic cross section can be obtained by convoluting the parton level cross section with parton distribution functions:

$$d\sigma(pp(\bar{p}) \rightarrow t\bar{t}) = \sum_{ij=q\bar{q}(gg)} \int_0^1 dx_1 \int_0^1 dx_2 (f_i(x_1, Q^2) f_j(x_2, Q^2) + i \longleftrightarrow j) d\hat{\sigma}_{ij} \quad (6)$$

where  $f_i(x, Q^2)$  are the parton distribution functions (PDF's). The parton distribution functions of CTEQ6L set [21] with the  $Q$ -scale is equal to the top quark mass are used to perform the calculations. The top quark mass has been taken to be 173 GeV.

Figures 1 depict the dependence of the relative change of the total  $t\bar{t}$  cross section originating from CMDM and CEDM at the Tevatron, LHC7, and LHC8. As it can be seen, the sensitivity of the cross section at the LHC to CMDM and CEDM is higher than the Tevatron rate. The left plot in Fig. 1 shows the dependence of the relative change of total cross section on  $\kappa$  when  $\tilde{\kappa} = 0$ . For positive values of  $\kappa$  in the range of around  $0 < \kappa < 0.9(1.6)$  for the LHC (Tevatron), the cross sections are suppressed. The  $t\bar{t}$  cross sections are decreased up to the level of 50% when  $0 < \kappa < 0.9(1.6)$  for the LHC (Tevatron). As discussed previously and can be seen in the right plot of Fig.1, the cross section is symmetric when  $\tilde{\kappa} \rightarrow -\tilde{\kappa}$ .

Any measured value of the  $t\bar{t}$  cross section significantly deviated from the SM predictions could lead to the existence of a non-zero value for CEDM and/or CMDM. The recent experimental measured values of the cross section of  $t\bar{t}$  at the LHC at the center-of-mass energy of 7 TeV (using  $1.1 \text{ fb}^{-1}$  of data) and Tevatron (obtained from  $4.6 \text{ fb}^{-1}$  of data) including all sources of uncertainties are [22],[23]:

$$\sigma(pp \rightarrow t\bar{t})_{\text{LHC}} = 164 \pm 14.2, \quad \sigma(p\bar{p} \rightarrow t\bar{t})_{\text{Tevatron}} = 7.5 \pm 0.48 \quad (7)$$

These measurements are in agreement with the standard model predictions which are 163 pb for the LHC7 and 7.08 pb for the Tevatron [24]. Figures 2 depict the Tevatron cross section versus the LHC cross section when  $\tilde{\kappa} = 0$  and  $\kappa$  is running (left) and when  $\kappa = 0$  and  $\tilde{\kappa}$  is running (right). The blue rectangle presents the current experimental uncertainties on the  $t\bar{t}$

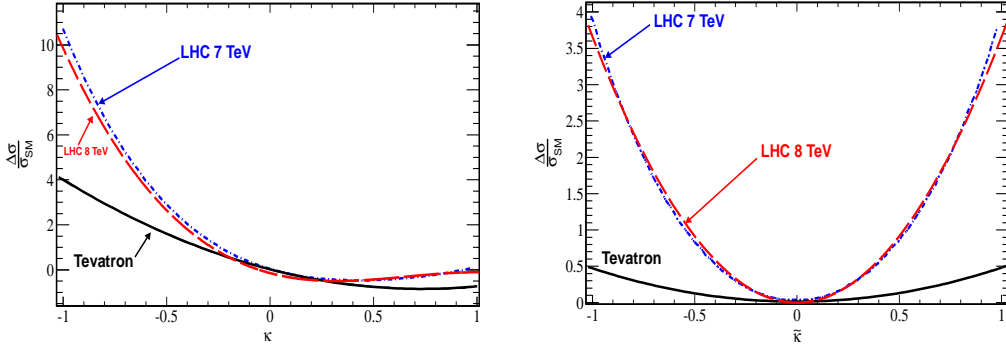


Figure 1: The relative change to the  $t\bar{t}$  production cross section at the Tevatron and LHC7 in terms of  $\kappa$  (left) and  $\tilde{\kappa}$  (right).

cross sections at the LHC and Tevatron. From Figs. 2, one can see and compare the sensitivity of the LHC and Tevatron cross sections to CEDM and CMDM.

Using the current measurements and the relative uncertainties, the following constraints are extracted:

$$\text{LHC7 : } -0.04 < \kappa < 0.98 , -0.15 < \tilde{\kappa} < 0.15 \quad (8)$$

$$\text{Tevatron : } -0.03 < \kappa < 1.5 , -0.37 < \tilde{\kappa} < 0.37$$

In obtaining the bounds on each anomalous coupling, the other has been set to zero. As it can be seen, the the cross section of LHC is more sensitive to the new interactions and provide tighter bounds with respect to the Tevatron. Assuming the measurement of the SM cross section experimentally with a relative uncertainty of 5%, the following limits could be obtained:

$$\text{LHC7 : } -0.02 < \kappa < 0.95 , -0.09 < \tilde{\kappa} < 0.09 \quad (9)$$

From fig.1, we conclude that the corrections that the  $t\bar{t}$  cross section receives from  $\kappa$  and  $\tilde{\kappa}$  are almost similar in proton-proton collisions at 7 TeV and 8 TeV.

In [6], it was shown that the shape of transverse momentum and rapidity of top (anti-top) quark are not sensitive to  $\tilde{\kappa}$ . While the top quark transverse momentum is sensitive to the sign of CMDM ( $\kappa$ ). In [13], the effects of CMDM and CEDM on the energy, transverse momentum, and angular distributions of lepton in top decay have been investigated. Except for the size , no change in shape is observed.

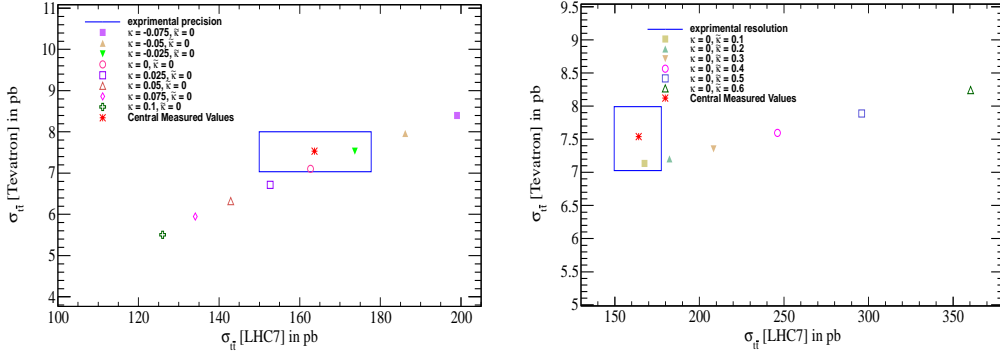


Figure 2: The  $t\bar{t}$  production cross sections at the Tevatron versus LHC7 when  $\kappa$  is running (left) and when  $\tilde{\kappa}$  is running (right). The current experimental resolution is presented by the blue rectangle.

### 3 The Contribution of Gluon-Gluon Fusion in $t\bar{t}$ Production

In spite of proton-proton collisions at the LHC, in the Tevatron in proton-antiproton collisions the main production mechanism of  $t\bar{t}$  is quark-antiquark annihilation. In particular, around 90% of the  $t\bar{t}$  cross section at the Tevatron is coming from the quark-antiquark annihilation. The fractions of  $t\bar{t}$  production from gluon-gluon fusion and quark-antiquark annihilation are strongly dependent on the choice of parton distribution functions [25]. Therefore, precise measurement of these fractions provide better understanding of parton distribution functions. Furthermore, there are several models beyond the standard model which directly affect the  $t\bar{t}$  production mechanism. The measurement of these fractions allow us to probe those models [26].

The CDF Collaboration has measured the gluon-gluon contribution to the top pair cross section at the Tevatron.

In order to measure the ratio  $R = \sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$ , some variables that are sensitive to the  $t\bar{t}$  production mechanism are used. Since the functional form of the cross section is different for gluon-gluon fusion from  $q\bar{q}$  annihilation, some variables could be found to distinguish between the production mechanisms.

For example, the cosine of the angle between the momentum of the top quark and the incoming proton direction, the velocity of the top quark are of the variables which are used to distinguish between the production mechanisms. Since top pair events with parallel top-quark spins come

exclusively from gluon-gluon production, the angular distributions of the top decay products show different behavior with respect to those coming from  $q\bar{q}$  annihilation. More details of the distinguishing variables are described in [27]. In [27], a measurement of the ratio of the  $t\bar{t}$  events produced through gluon-gluon fusion to the total  $t\bar{t}$  events is presented. Using around  $1 \text{ fb}^{-1}$  of data collected with the CDF detector and taking into account only semi-leptonic  $t\bar{t}$  events lead to:

$$R = \frac{\sigma(gg \rightarrow t\bar{t})}{\sigma(p\bar{p} \rightarrow t\bar{t})} = 0.07^{+0.15}_{-0.07}. \quad (10)$$

Figs.3 depict the relative correction due to non-zero values of CEDM and CMDM to the fraction of gluon-gluon fusion in  $t\bar{t}$  production at the LHC7 and Tevatron. As it can be seen,  $\Delta R = (R(\kappa, \tilde{\kappa}) - R_{SM})/R_{SM}$  is significantly sensitive to  $\kappa$  and  $\tilde{\kappa}$  at the Tevatron. While at the LHC, the presence of CEDM and CMDM does not cause to considerable change in the contribution of gluon-gluon fusion in top pair production.

The present Tevatron measurement of the ratio  $R$  gives the following limits:

$$-1.1 < \kappa < 0.6, \quad -0.8 < \tilde{\kappa} < 0.8$$

The current Tevatron measurement is based on around  $1 \text{ fb}^{-1}$  of data. However, Tevatron has taken more than  $5 \text{ fb}^{-1}$  of data before shut down. The analysis of full data improves the measurement of  $R$ , for example a future measurement of the SM expectation for  $R$  with 10% uncertainty gives:

$$-0.15 < \kappa < 0.3, \quad -0.18 < \tilde{\kappa} < 0.18$$

So far, there is no measurement of  $R$  at the LHC. Assuming the SM prediction with 10% uncertainty leads to:

$$-0.3 < \kappa < 0.25, \quad -0.45 < \tilde{\kappa} < 0.45$$

In fig.4, we present the allowed region in the  $(\kappa, \tilde{\kappa})$  plane which satisfies the LHC cross section measurement and the measured  $R$  by the CDF detector at the Tevatron. The region allowed by cross sections measured by CMS, ATLAS, CDF, and D0 collaborations altogether has been presented in [13]. The combination of all of these experiments leads to much tighter limits in the  $(\kappa, \tilde{\kappa})$  plane.



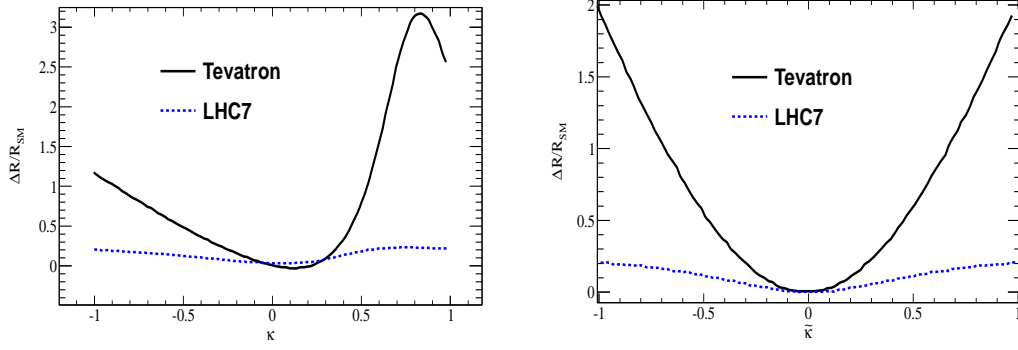


Figure 3: The relative correction originating from CDM and CEDM to the ratio of  $\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$ .

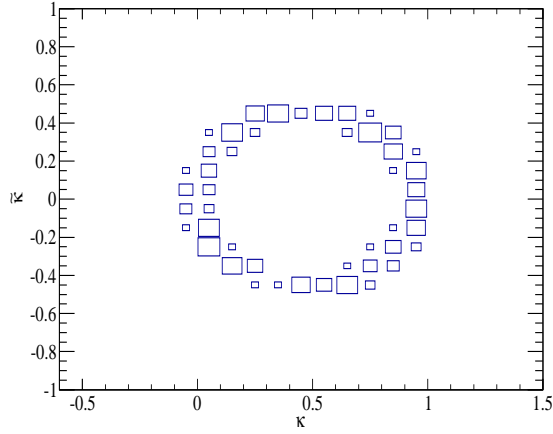


Figure 4: The allowed region in the plane of  $\kappa, \tilde{\kappa}$  which satisfies the LHC cross section measurement and the measured ratio  $R = \sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$ .

	$\sigma_{\text{Tevatron}}$	$\sigma_{\text{LHC}}$	ratio $R$	$A_C$
$\kappa$	$-0.03 < \kappa < 1.5$	$-0.04 < \kappa < 0.98$	$-1.1 < \kappa < 0.6$	$-1.72 < \kappa < 2.02$
$\tilde{\kappa}$	$-0.37 < \tilde{\kappa} < 0.37$	$-0.15 < \tilde{\kappa} < 0.15$	$-0.8 < \tilde{\kappa} < 0.8$	-

Table 1: Comparison of the bounds extracted from Tevatron, LHC, gluon-gluon fusion ratio, and  $A_C$  on  $\kappa$  and  $\tilde{\kappa}$ .

## 4 Charge Asymmetry

Since the initial state of the collisions at the LHC is proton-proton which is symmetric; it is expected that the rapidity distributions of top quarks and top antiquarks are symmetrical around  $y = 0$ . However, at the LHC the initial state quarks are abundantly valence quarks, while always the antiquarks are sea quarks. The larger average momentum fraction of the quarks leads to an excess in production of top quarks in the forward directions. This fact causes to a broader rapidity distribution of top quarks in the SM with respect to the produced top antiquarks and therefore a charge asymmetry is produced [28].

One way to define the top charge asymmetry is as the following:

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)} \quad (11)$$

The NLO prediction for the charge asymmetry at a centre-of-mass energy of 7 TeV is  $A_C(\text{theory}) = 0.0115 \pm 0.0006$  [28]. The existence of new sources of physics with different vector and axial-vector couplings to top quarks and antiquarks could enhance these asymmetries [28]. The recent measured value by the CMS Collaboration using  $4.7 \text{ fb}^{-1}$  of data is  $A_C = 0.004 \pm 0.016$  [29]. The uncertainty comprises all sources of uncertainties.

Fig.5 shows the dependence of  $A_C$  on CMDM ( $\kappa$ ). The dashed line is the upper limit on  $A_C$  measured by the CMS collaboration at the LHC. This provides very loose bounds on  $\kappa$ . Charge asymmetry is almost insensitive to  $\tilde{\kappa}$  and therefore does not give notable limits on  $\tilde{\kappa}$ .

Finally, in Table 1 we compare the limits obtained from the LHC and Tevatron cross sections, the ratio of gluon-gluon fusion in top pair production rate ( $R$ ), and the charge asymmetry. The upper limit on  $\kappa$  from  $R$  is tighter than the ones obtained from cross sections. Charge asymmetry do not show large sensitivity to CEDM and CMDM.

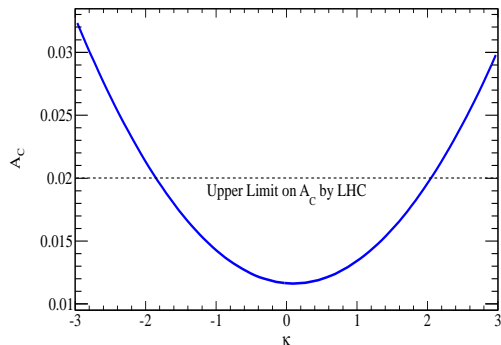


Figure 5: Charge asymmetry as a function of  $\kappa$  and the upper limit on charge asymmetry measured by the CMS experiment.

## 5 Conclusions

We have studied the effects of anomalous top quark coupling with gluon on the fraction of gluon-gluon fusion in the  $t\bar{t}$  production cross section at the Tevatron and LHC. We found that the fraction of gluon-gluon fusion in  $t\bar{t}$  production rate ( $R$ ) at the Tevatron is more sensitive to CEDM and CMDM than the LHC. It is shown that the precise enough measurement of  $R$  is able to provide bounds on CMDM ( $\kappa$ ) and CEDM( $\tilde{\kappa}$ ) comparable with the bounds from cross sections. We also examined the sensitivity of charge asymmetry ( $A_C$ ) in  $t\bar{t}$  events at the LHC to  $\kappa$  and  $\tilde{\kappa}$ . No considerable deviation is found from the presence of  $\tilde{\kappa}$ . The current limit on  $A_C$  gives loose bound on  $\kappa$ .

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